Report on Satellite anomalies by request of Mathias B. Dannevig

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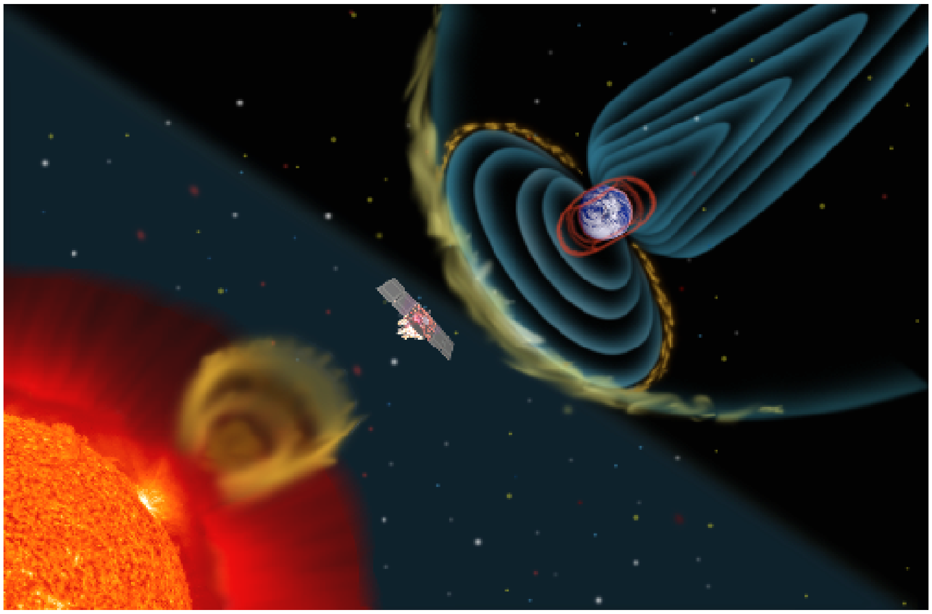

Solar Eruptions and Effects on the Earth's Environment – Satellite Anomalies and Space Weather Forecast –

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1 Introduction

The response of our space environment to the constantly changing Sun is known as *"Space Weather"*. Most of the time space weather is of little concern in our everyday lives. However, when the space environment is disturbed by the variable outputs of the Sun, technologies that we depend on both in orbit and on the ground can be affected. Some of the most dramatic space weather effects occur in association with eruptions of material from the solar atmosphere into interplanetary space. Thus, our space weather is a consequence of the behavior of the Sun, the nature of Earth's magnetic field and atmosphere, and our location in the solar system.

The increasing deployment of radiation-, current-, and field-sensitive technological systems over the last few decades and the increasing presence of complex systems in space combine to make society more vulnerable to solar-terrestrial disturbances. This has been emphasized by the large number of problems associated with the severe magnetic storms between 1989 and 1991 as the 11-year solar activity cycle peaked.

The Sun and its atmosphere are always changing, in a sense having weather of their own. The Sun undergoes long-term (decade or more) "climate-like" variations such as the roughly 11-year solar cycle. This cycle first showed itself in the number of sunspots counted on the solar surface as observed from the ground.

Sunspots are dark concentrations of intense magnetic fields emerging from below the Sun's surface. They were first observed in the west by Galileo in 1610 shortly after he started observing the sun with his new telescope. Daily observations were started at the Zurich Observatory in 1749 and with the addition of other observatories continuous observations were obtained starting in 1849. The number of sunspots appearing on the the solar surface were soon observed to vary with time in an approximately 11-year cycle. This regular increase and decrease in the level of solar activity, is called the solar cycle.

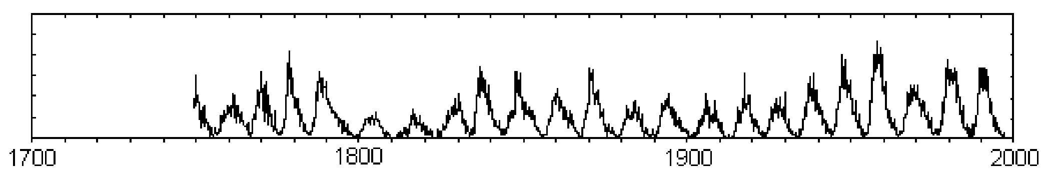

Figure 1: The variation of the solar activity represented by the monthly average sunspot number

Figure 1 shows the solar activity variations since 1749 measured by the fractional area of the Sun covered by sunspots at any time. The time between successive maxima or minima in the sunspot number is between 9.5 and 11 years. Periods of large sunspot number are called "solar maximum" periods, while periods of low sunspot number are called "solar minimum" periods.

As can be seen from Figure 1 the level of activity within each cycle can vary considerable. This can also be seen in Figure 2 showing the monthly (blue) end monthly smoothed (red) sunspot numbers for the four last cycles. The variations in the monthly measurements comes from the modulation of the solar rotation.

Although sunspots themselves (Figure 3, left panel) produce only minor effects on solar emissions, the magnetic activity that accompanies the sunspots can produce dramatic changes in the ultraviolet and soft x-ray emission levels. Recent space observations have revealed that the complexes of sunspots called active regions are the main source of long-lived solar features with enhanced

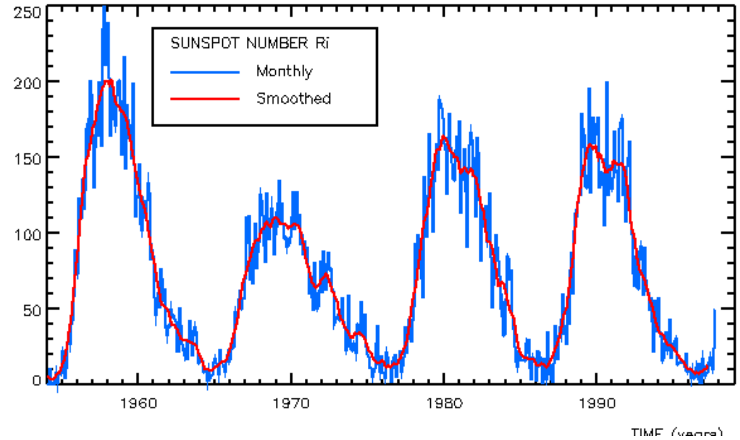

Figure 2: The variation of the solar activity for the four last cycles (Courtesy Royal Observatory of Belgium).

ultraviolet and x-ray emissions (Figure 3, right panel). Solar gas, confined by the strong active-region magnetic fields into loop-like structures, is heated to temperatures of millions of degrees. During times of maximum solar activity, the average level of solar ultraviolet emission can increase to several times the quiet Sun level, while the x-ray intensity shows even greater enhancements. Since active regions usually last longer than the 27-day solar rotation period, the radiations they emit also vary periodically on this time scale.

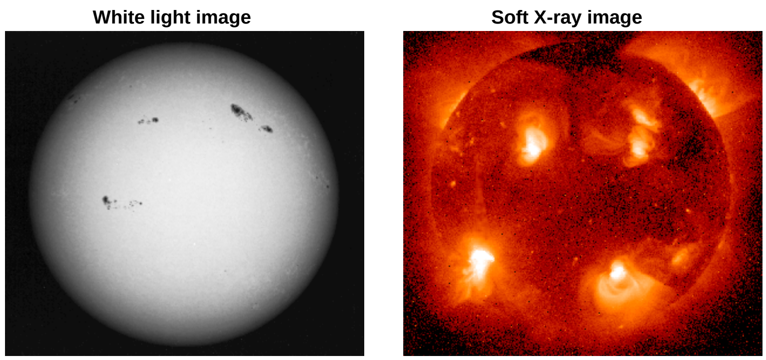

Figure 3: The Sun observed in white light (left) from the ground and in soft X-ray (right) from space. The apparent difference is striking. (courtesy of Lockheed-Martin Solar and Astrophysics Laboratory).

The 12 x-ray images of the Sun's atmosphere, obtained between 1991 and 1995 at 120 day increments, provide a dramatic view of how the corona changes during the waning part of the solar cycle (Figure 4). The x-ray Sun appears completely different from the Sun we see in the sky as was illustrated in Figure 3. X-rays are only emitted by very hot gases. The upper atmosphere of the Sun, where temperatures reaches a few millions degrees, is hot enough to emit x-rays, while the much cooler surface of the sun, at 6000 degrees C, is not. As a result, an x-ray image reveals a bright glow for the corona and a black disk for the surface of the Sun. In the corona, the shape and character of the hot gases are controlled by the magnetic fields, just as beads move with string upon which they are threaded. As the solar activity cycle progresses from maximum to minimum, the Sun's magnetic field changes from a complex structure to a simpler configuration with fewer fields. Since the Sun's hot gases are controlled by these fields, the x-ray images reflect this global change, with an overall decrease in brightness by 100 times.

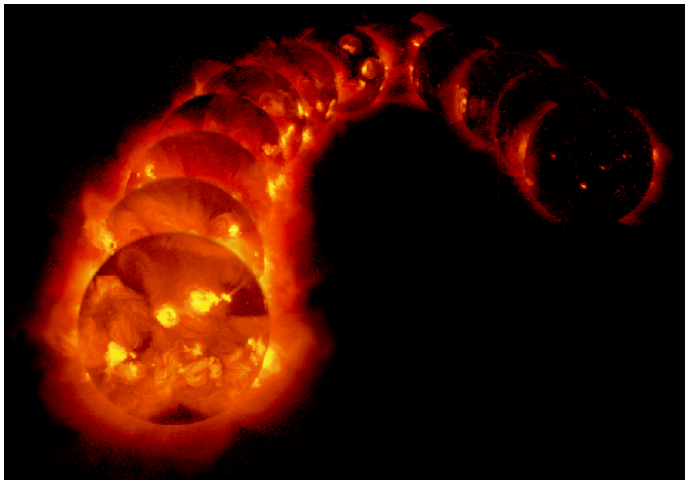

Figure 4: Collage of x-ray images of the Sun obtained on the Yohkoh satellite between 1991 and 1995 at 120-day intervals, showing the evolution in the appearance of the Sun in these emissions from active to quiet times (courtesy of Lockheed-Martin Solar and Astrophysics Laboratory).

The high temperature of the solar upper atmosphere generates an outward flow of the ionized coronal gas or plasma away from the Sun at typical speeds ranging from 400 to 800 kilometers per second. This outflow is known as the "solar wind" The solar wind flows around obstacles such as planets, but those planets with their own magnetic fields respond in specific ways. Earth's magnetic field is very similar to the pattern formed when iron filings align around a bar magnet. Under the influence of the solar wind, these magnetic field lines are compressed in the Sunward direction and stretched out in the downwind direction (see illustration on front page). This creates the magnetosphere, a complex, teardrop-shaped cavity around Earth. The Van Allen radiation belts are within this cavity, as is the ionosphere, a layer of Earth's upper atmosphere where photo ionization by solar x-rays and extreme ultraviolet rays creates free electrons. The Earth's magnetic field senses the solar wind, its speed, density, and magnetic field. Because the solar wind varies over time scales as short as seconds, the interface that separates interplanetary space from the magnetosphere is very dynamic. Normally this interface, called the magnetopause, lies at a distance equivalent to about 10 Earth radii in the direction of the Sun. However, during episodes of elevated solar wind density or velocity, the magnetopause can be pushed inward to within 6.6 Earth radii (the altitude of geosynchronous satellites). As the magnetosphere extracts energy from the solar wind, internal processes produce geomagnetic storms.

In this report the different effects on the Earth's environment are discussed with emphasis on the effects on satellites. The current status of the space weather forecast as it exist today and what we can expect in the future is discussed. Examples of recent solar storms as observed with the Solar and Heliospheric Observatory are given to illustrated the impact such observations could have for future space weather forecasting.

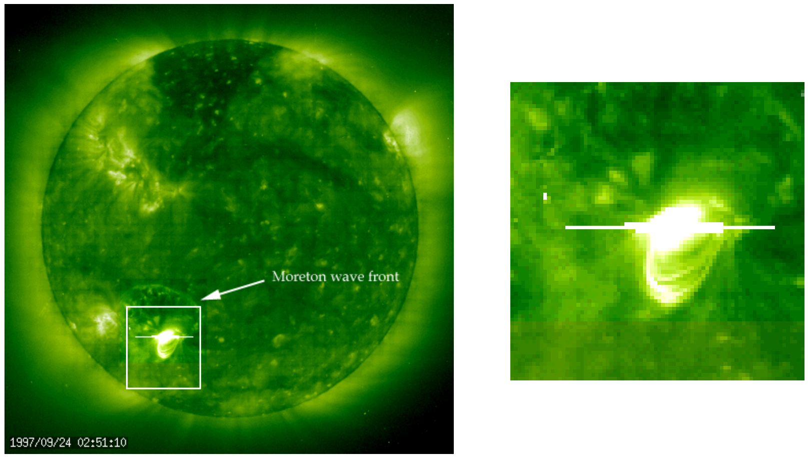

Figure 5: Image of the Sun from the SOHO Extreme ultraviolet Imaging Telescope (EIT) showing an example of a flare event (24 September 1997). The right panel shows the flare site where one can see several bright arches or loops. The horizontal bright line is due to saturation of the detector because of the extreme enhancement of the UV radiation (Courtesy of SOHO/EIT consortium).

2 Solar Storms

Space weather disturbances are generally caused by what are effectively "solar storms". There are two different types of events on the Sun that triggers disturbances in the Earth's environment. One type is called a *solar flare* because the brightening of a small area on the Sun heralds its occurrence. The other type of storm is called a *coronal mass ejection (CME)*.

2.1 Solar Flares

When a flare occur on the Sun (See Figure 5) a large increase in electromagnetic radiation follows (this is photons with energies in the UV and x-ray portion of the energy spectrum). The energetic electromagnetic radiation bursts accompanying flares on the Sun travel at the speed of light, and so arrive at Earth just eight minutes after leaving the flare site, well ahead of any particles or coronal material associated with the flare. Moreover, unlike the electrons and ions of the solar wind plasma and the solar energetic particle populations, the passage of electromagnetic waves is not affected by the presence of Earth's magnetic field. The direct response of the upper atmosphere to a burst of solar flare ultraviolet and x-ray emissions is a temporary increase in ionization (as well as temperature) in the sunlit hemisphere of minutes to hours duration called a *sudden ionospheric disturbance* (SID). The increase of ionization below 100-km altitudes is especially significant on these occasions.

In generall the geomagnetic storms and increased solar ultraviolet emission heat the Earth's upper atmosphere, causing it to expand. The heated air rises, and the density at the orbit of satellites up to about 1000 km increases significantly. This results in increased drag on satellites in space, causing them to slow and change orbit slightly. Unless low-Earth-orbit satellites are routinely boosted to higher orbits, they slowly fall, and eventually burn up in Earth's atmosphere.

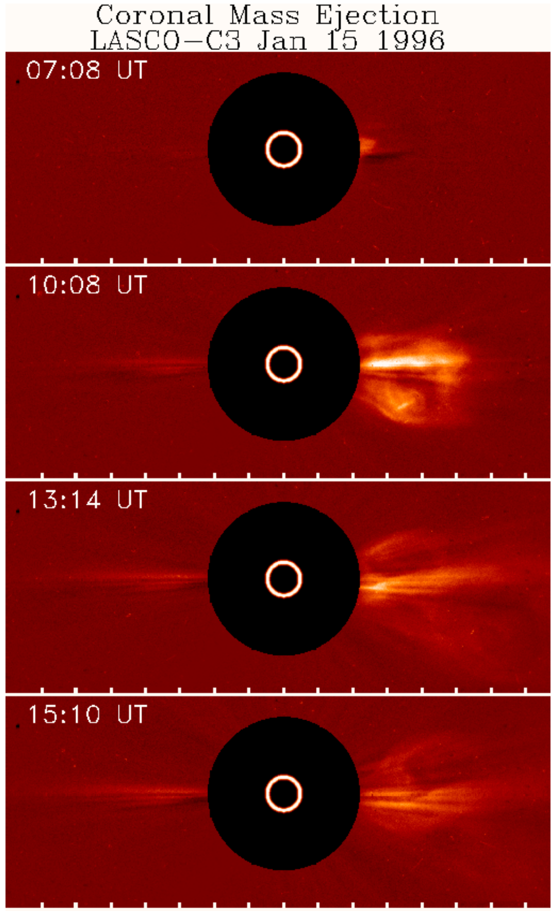

Figure 6: Large coronal mass ejection (CME) as recorded by the SOHO/LASCO C3 coronagraph on 15 January 1996. The ejected material (seen to the right of the blocked Sun) moved with a velocity over 1000 km/s. LASCO is blocking out the brightness of the sun itself (an artificial solar eclipse). The circle in the images shows where the sun would be if it wasn't blocked out. (Courtesy of SOHO/LASCO consortium.)

2.2 Coronal Mass Ejections - CME's

However, not all solar flares result in magnetic storms, and, even more significantly, not all geomagnetic storms can be associated with solar flares. Some of the most dramatic space weather effects occur in association with eruptions of material from the solar atmosphere into interplanetary space. These eruptions are known as coronal mass ejections, or CMEs. Such eruptions are sometimes associated with flares and sometimes not and they now appear to be a primary cause of geomagnetic activity [Kahler, 1992; Gosling, 1993].

CME's is believed to be caused by sudden disruptions in the Sun's own magnetic field. These magnetic field lines stretch and twist like titanic rubber bands until they snap. A large CME can contain 1.0×10^7 grams (a billion tons) of matter that can reach speeds up to 2000 kilometers per second, considerably greater than the normal solar wind speeds of about 400 kilometers per second. Thus, unlike the solar flares which emits enhanced UV/x-ray radiation the CME's results in a "cloud" of charged particles (ions and electrons). This cloud often brings with it parts of the solar magnetic fields and is often named a *magnetic cloud*. The charged particles and the magnetic field will interact with the Earth's magnetic field when the cloud reaches the Earth's orbit.

CMEs are not easily detectable unless they occur on the limb of the sun (see Figure 6). CMEs that are ejected toward the Earth produce geomagnetic activity when the associated shock front arrives. The severity of the storm is related to the polarity of the north-south component of the interplanetary magnetic field (IMF) as well as the velocity of the magnetic cloud from the CME.

Geomagnetic activity in the Earth's environment can also be caused by solar wind fluctuations due to large scale structures on the sun called coronal holes. This is regions of the Sun's corona where the density is lower than average, and the temperature and associated solar wind expansion velocity are higher than average. Their name reflects the fact that they appear dark in x-ray images of the corona due to their low density. Coronal holes are most common on the poles (called polar coronal holes), but sometimes they can extend towards the equator. The high solar wind velocity from these areas on the Sun often introduces minor geomagnetic activity.

3 Space Weather Effects on the Earth's Environment

The most common effects on the Earth's environment due to geomagnetic activity are briefly discussed below with emphasis on the impact on satellites. We refer the reader to Allen and Wilkinson, (1993) for more details on this topic.

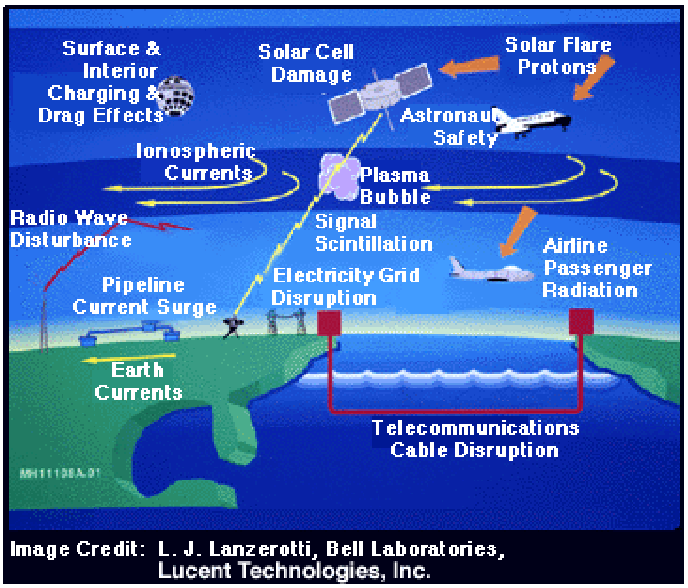

Figure 7: Illustration showing samples of possible effects from solar eruptions and flares.

3.1 Hazards to Humans in Space

Energetic solar protons are a radiation health hazard for astronauts on manned space flights. The arrival time in the near-Earth environment can begin within tens of minutes of the eruption of a solar flare. While low inclination orbits take advantage of the shielding of the Earth's magnetic field, high inclination orbits place the Shuttle outside normal rigidity cut-offs, allowing increased dosages. The coupling of the US Space Station program with the Russian MIR station will result in still higher inclinations. Prediction and monitoring of solar flares and CMEs provide essential safety constraints

The radiation exposure to passengers in high-altitude aircraft is also of concern. Although the residual atmosphere above an aircraft provides a measure of protection from cosmic rays and solar energetic particles that enter the magnetosphere, there is still concern for flights on polar routes during major solar particle events. Radiation sensors on Concorde supersonic jets showed that passengers and crew sometimes received a radiation dose equivalent to a chest X-ray [Allen and Wilkinson, 1993]. To reduce the risk to aircraft crews and passengers, and reduce risk to the aircraft, routine forecasts and alerts are sent through the Federal Aviation Administration so that a flight in potential danger can consider what course of action to take to minimize radiation exposure.

3.2 Effects on Communications Systems

Shortwave radio communication at HF frequencies (3-30 megahertz), which is still extensively used by the military and for overseas broadcasting in various countries, depends upon the reflection of signals from Earth's ionosphere. The effects of strong solar storm are an increase in the local electron density in the ionosphere which can cause a total communications blackout.

The ionospheric changes that occur during disturbed times also increase the incidence of electron density irregularities, leading to sometimes severe variations in the phase strength of signals sent from the ground to satellites at VHF and UHF frequencies (30 megahertz to 3 gigahertz). In summary, space weather-related disruptions to communication systems have wide-ranging effects from social interactions to economic transactions on a global level to intelligence and surveillance activities.

3.3 Effects on Geomagnetic Surveys

Geomagnetic surveys are important tools in the commercial exploration of natural resources (e.g. search for oil and gas). However, space weather-related perturbations can create signals in survey data that can be mistaken for signatures of subsurface resources. Survey schedules or operations must be modified, often suddenly and with significant cost impact, to avoid this contamination of the survey data.

3.4 Effects on Navigation Systems

Systems such as LORAN and OMEGA are adversely affected when solar activity disrupts their radio wavelengths. The OMEGA system consists of eight transmitters located through out the world. Airplanes and ships use the very low frequency signals from these transmitters to determine their positions. During solar events and geomagnetic storms, the system can give navigators information that is inaccurate by as much as several miles. If navigators are alerted that a proton event or geomagnetic storm is in progress, they can switch to a backup system.

The same disturbance-related changes in Earth's ionosphere that affect communications introduce changes in the time it takes signals to traverse the ionosphere. The abnormal time delays introduce position errors and decrease the accuracy and reliability of the Global Positioning System

(GPS), which is used for many range-finding and navigational purposes [e.g. Heroux and Kleusberg, 1989].

3.5 Aurora

The aurora is a dynamic and delicate visual manifestation of solar-induced geomagnetic storms. The solar wind energizes electrons and ions in the magnetosphere. These particles usually enter Earth's upper atmosphere near the polar regions. When the particles strike the molecules and atoms of the thin, high atmosphere, some of them start to glow in different colors.

3.6 Effects of pipelines

Space weather-induced currents similarly flow in long conductors on the ground such as oil pipelines. These currents create galvanic effects that lead to rapid corrosion at the pipeline joints if they are not properly grounded. Such corrosion requires expensive repairs or can lead to permanent damage.

3.7 Effects on Power Systems

Electric power systems on the ground can be affected by the enhanced currents that flow in the magnetosphere-ionosphere system during geomagnetic disturbances. Such disturbances can induce near DC currents (Geomagnetically Induced Currents, GIC) in long power lines. For instance, during the March 13, 1989, storm, GIC caused a complete shutdown of the Hydro-Quebec power grid resulting in a nine hour power outage. The power pools that serve the entire northeastern United States came uncomfortably close to a cascading system collapse [Kappenman, 1993]. This particular event is discussed in more detail in section 4.1

3.8 Satellites

Space weather affects satellite missions in a variety of ways, depending on the orbit and satellite function. Our society depends on satellites for weather information, communications, navigation, exploration, search and rescue, research, and defense systems. The impact of satellite system failures is more far- reaching than ever before, and the trend will almost certainly continue at an increasing rate.

Energetic particles that originate from the sun and from the Earth's magnetosphere continually impact the surfaces of spacecraft. Highly energetic particles penetrate to electronic components, causing bit-flips in a chain of electronic signals that can result in spurious commands (*phantom commands*) appearing to spacecraft systems as directions from the ground. In addition one can experience erroneous data from the onboard instruments. These spurious commands have caused major failures to satellite systems and even causing the craft to point away from the earth direction. Many failures could most probably have been avoided had ground controllers known in advance of impending particle hazards. During large solar storms certain satellite operators were not even aware of satellite anomalies because their communication links to the satellites were inoperable due to the geomagnetic storm itself. Less energetic particles contribute to a variety of spacecraft surface charging problems, especially during periods of high geomagnetic activity. In addition, energetic electrons responsible for *deep dielectric charging*[1] can degrade the useful lifetime of internal components.

The upper atmosphere becomes inflated if it is heated by extra energy sources such as auroral particles and enhanced resistive ionospheric currents. The resulting increased atmospheric densities at 300-500-kilometers altitudes significantly increase the number of microscopic collisions between the satellite and the surrounding gas particles. This increased "satellite drag" can alter an orbit enough that the satellite is temporarily "lost" to communications links. At times, these effects may be sufficiently severe as to cause premature re-entry of orbiting objects, such as Skylab in 1979 and Solar Maximum Mission in 1989.

The failure of the the Japanese geostationary telecommunications satellite CS-3b (in 1989) and the Canadian Anik satellite (January 1994) highlighted that many tens of billions of dollars are invested in satellite systems that are potentially at risk. More than 200 commercial and military satellites are estimated to be in geosynchronous orbit from various worldwide sources. Assuming that each may cost of the order of 200 million USD, that adds up to over 40 billion USD in hardware in geosynchronous orbit alone.

Data on spacecraft anomalies are maintained by the National Oceanic and Atmospheric Administration (NOAA) at its National Geophysical Data Center (NGDC) in Boulder, Colorado. However, it is often difficult to obtain information on satellite anomalies since many satellite operators are not willing to share this information. For a period of 25 days in March 1989 (in connection with a severe magnetic storm) 46 instances of operational disturbances are listed. The majority of these are diagnosed to be from electrostatic discharge from spacecraft charging. Again, one should note that this list was made from a subset of satellites whose operators are willing to provide information. The total problem is much larger. Maynard (1995) indicates that more than 9000 anomalies covering the time period from 1970 to 1995 have occured.

4 Space Weather forecast - where are we?

The Space Environment Center (SEC) in Boulder, Colorado conducts research in solar-terrestrial physics, develops techniques for forecasting solar and geophysical disturbances, provides real-time monitoring and forecasting of solar and geophysical events, and prepares data to be archived by NOAA's National Geophysical Data Center. SEC's Space Weather Operations branch (SWO) is the national and world warning center for disturbances that can affect people and equipment working in the space environment. Jointly operated by NOAA and the U.S. Air Force, SWO provides forecasts and warnings of solar and geomagnetic activity to users in government, industry, and the private sector.

The current space weather forecasting is based on observations of the Sun, both from ground and space. In addition several satellites monitors the Earth's environment itself by measuring key physical parameters. Images of the Sun in visible light or by use of special filters gives information about occuring flares or the possibility of flares in the near future. The latter involves a great uncertainty since the forecast is based on a visual interpretation of the current structure of active regions on the visible hemisphere of the Sun. Some types of configurations of the magnetic field of the active regions have a larger possibility of creating a flare than others. However, it is impossible

[1]deep dielectric charging: The addition of electric charge deep within a dielectric component of an electronic system by the impact of an energetic charged particle. This charging can disrupt the electronic signals of the system.

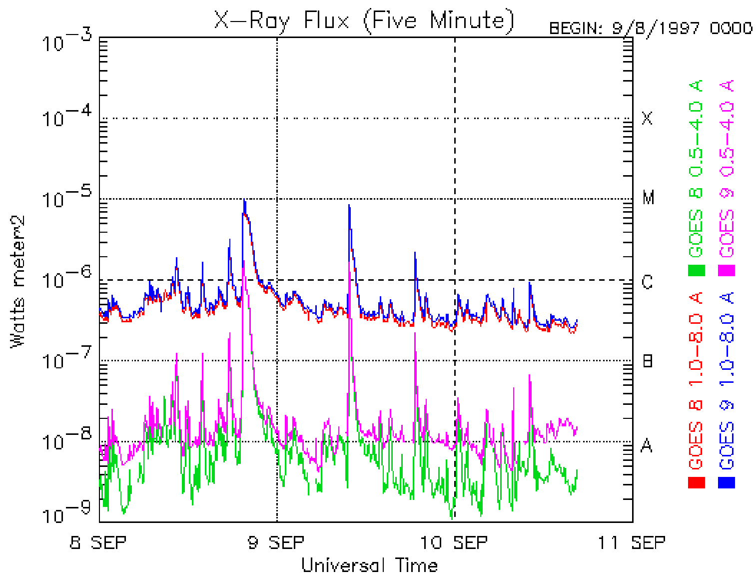

Figure 8: X-ray measurements from the GOES 8 and 9 satellites. The upper plot shows data from 0.1 to 0.8 nanometers, the lower plot 0.05 to 0.4 nanometers. Solar flares shows up like strong enhancements in these plots. The scale on the right indicates the classification of the flare. Above M is a large flare, above X is a very large flare that will certainly be felt at Earth. (courtesy of Space Environment Center).

to give a time line for when a flare might occur. Space born detectors also monitors the radiative output from the Sun. In particular the GOES satellites (8 and 9) provides measurements of the X-ray flux as shown in Figure 8. A few minutes after a flare occur (even if the ground based observatories missed the flare due to night time or bad weather) the the enhanced flux from the Sun gives the first indication of the strength of the flare. The X-ray plot in Figure 8 shows 3 days of 5-minute solar X-ray flux values measured on the GOES 8 and 9 satellites. The upper plot shows data from 0.1 to 0.8 nanometer energy band, the lower plot 0.05 to 0.4 nanometers. A number of relatively small flares occured within the displayed 3 day period. The flare scale is based on the intensity of x-rays from the sun. Class C is a small event, Class M is 10 times stronger, and Class X is 100 times stronger than Class C.

SEC also provides an overview of the current geosynchronous satellite environment combining both satellite and ground-based data. The current conditions (as of September 10, 1997 and the last three days) is shown in Figure 9. The top panel shows the high velocity proton flux in the Earth's environment. If the red line raise above the white dashes line there is an enhanced possibility of spacecraft damage. The next panel gives the current electron flux and warning is issued when the purple and/or the red lines are above the white dashed line. On September 10 there was an enhanced possibility of spacecraft charging based on the data in Figure 9. The third panel illustrated the current magnetic field (and it's direction) while the lower panel indicates the general level of space weather disturbances near Earth (the Planetary K index). Values plotted in red (above 6) indicates storm conditions. At a K of 6, satellites begin to experience a noticeable increase in atmospheric drag resulting in changes to their orbits. At K of 6 or 7, electric power systems begin to notice the effects. At K of 6, the aurora borealis is frequently visible over the northern United States. At K of 7 it may be visible to about the middle of the US. Although the data are of interest to the

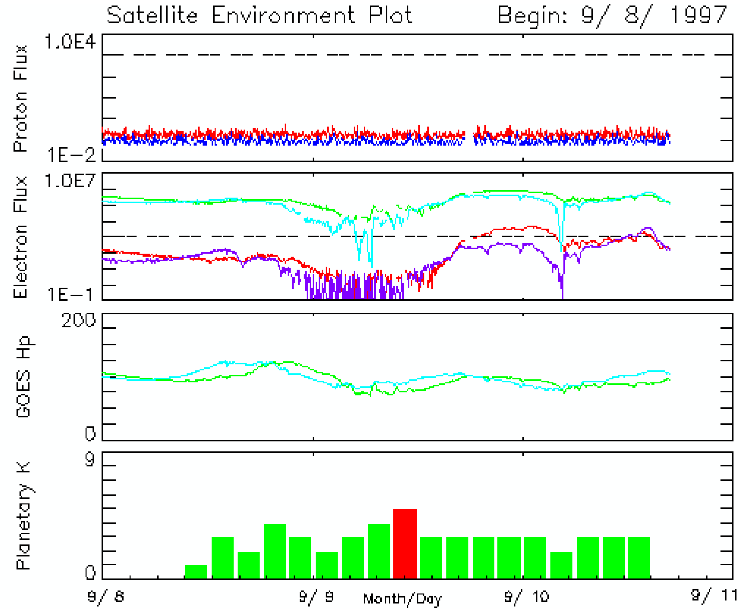

Figure 9: The satellite environment plot which gives an overview of the current geosynchronous satellite environment. See text for more information. (courtesy of Space Environment Center).

satellite community, they do not include all parameters and energy ranges known to be associated with satellite anomalies.

Even if flares on the Sun are observed, either by ground based observatories or by the GOES satellites (X-ray enhancements) it is very hard to estimates the expected effects on the Earth's environment. Also, as mentioned, not all flares are associated with geomagnetic storm. Real time observations of CME's is a much better tool for monitoring the space weather. But even if one do observe a CME directed toward the Earth the enormous distance to the Sun introduces a large uncertainty in the advance forecast. First of all the strength and the velocity of the particle/magnetic cloud is very difficult to determine accurately based on the CME observations. Secondly the characteristics and the structural dynamics of the particle cloud as it transit across interplanetary space is still poorly understood and can only be reexamined once it arrives at satellites near the Earth.

A key to accurate, short–term forecasting of new disturbances is continuous, real-time solar wind observations. Data obtained at the libration point (240 Earth radii upstream), where the Earth's gravitational pull is balanced by that of the Sun, provide a 30 to 50 minute warning of when a shock or disturbance in the solar wind will encounter the Earth's magnetosphere. The precise time depends on the solar wind velocity which can be measured by the satellites. NASA launched the WIND spacecraft in November, 1994, to investigate and monitor the solar wind as part of the International Solar Terrestrial Physics Program (ISTP). It is in a double lunar swing-by orbit, using synchronized close passages by the moon to constantly change the orbit in order to keep it in front of the Earth. However, the most dramatic forecast improvement was achieved after the launch of the satellites SOHO (1995) and ACE (1997). As will be discussed below these observatories have improved our ability to both study and understand the physical processes involved in such events and to increase the accuracy of advanced forecasts. They are both located in the Lagrangian point L1 as shown in Figure 10. This locations place the satellites outside the Earth's shielding magnetic fields so that the solar wind particles can be measured directly. The satellites also experiences

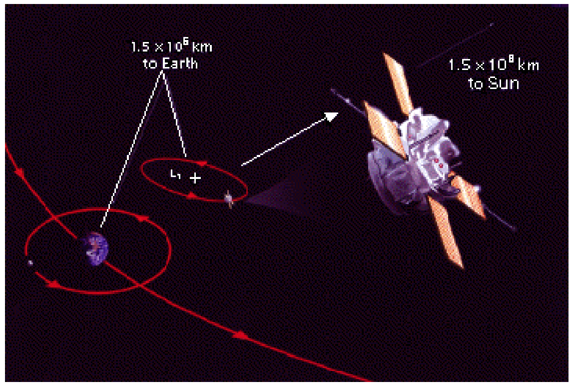

Figure 10: The halo-orbit around the Lagrangian point L1 provides an uninterrupted view of the Sun. This libration point follows the Earth's yearly orbit around the Sun.

continuously daylight and can observe the Sun and the solar wind 24 hours a day. All previous solar observatories have orbited the Earth, from where their observations were periodically interrupted as our planet 'eclipsed' the Sun. Since several Norwegian scientist as well as Norwegian industry are involved in instruments on SOHO a short overview of this project is given below.

4.1 The SOHO satellite

SOHO is designed to study the internal structure of the Sun, its extensive outer atmosphere and the origin of the solar wind, the stream of highly ionized gas that blows continuously outward through the Solar System. SOHO was launched on December 2, 1995 and after a 3 month cruise phase to the Lagrangian point L1 it has been been operating since early 1995. SOHO now gives astronomers their best view yet of solar storms and the solar wind flowing from the sun. The SOHO project is being carried out by the European Space Agency (ESA) and the US National Aeronautics and Space Administration (NASA) as a cooperative effort between the two agencies (Domingo, Fleck, and Poland 1995).

The SOHO spacecraft was built in Europe by an industry team led by Matra, and instruments were provided by European and American scientists. There are nine European Principal Investigators (PI's) and three American ones. Large engineering teams and more than 200 co-investigators from many institutions supported the PI's in the development of the instruments and in the preparation of their operations and data analysis. NASA is responsible for the launch and mission operations. Large radio dishes around the world which form NASA's Deep Space Network are used to track the spacecraft beyond the Earth's orbit. Mission control and science operation are based at Goddard Space Flight Center in Maryland.

The Norwegian contributions to one of the main instruments on SOHO included a) manufacturing and delivery of the Electrical Ground Support Equipment (EGSE), b) preparation for the operational phase, i.e. defining observing programs, operations procedures, and procedures for science analysis including the quick look software for the instrument, and c) participation in the daily operation of two of the instruments from NASA Goddard Space Flight Center. In addition Norwegian industry have delivered hardware components to the spacecraft.

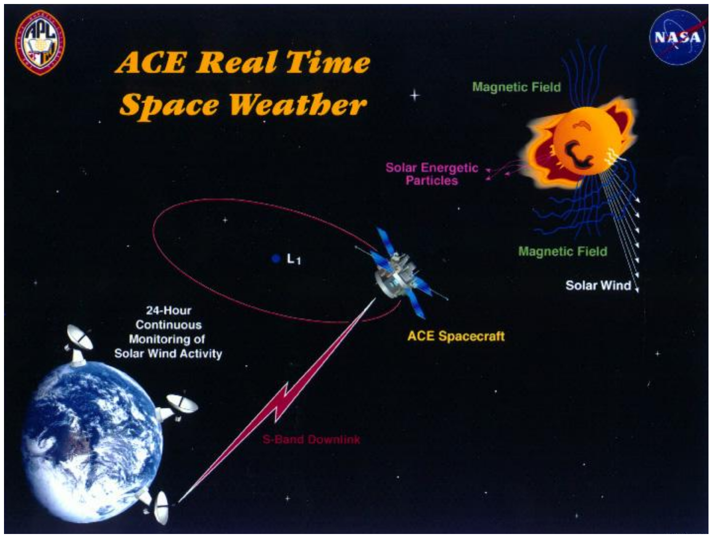

Figure 11: The ACE satellite provides continuously warning of enhancements of the solar wind and will improve the surveillance of solar storms (Courtesy of Johns Hopkins University Applied Physics Laboratory).

4.2 The ACE satellite

NASAs Advanced Composition Explorer (ACE) satellite was launched August 25 1997 to be inserted into a halo orbit around Lagrangian point L1 (Figure 11). The primary purpose of ACE is to determine and compare the isotopic and elemental composition of several distinct samples of matter, including the solar corona, the interplanetary medium, the local interstellar medium, and Galactic matter. It will also measure the local interplanetary magnetic field (IMF) direction and magnitude. With solar wind speeds and structures as we presently understand them, this satellite will on average provide warnings of severe storm events typically an hour in advance. ACE is operated from the same building at Goddard Space Flight Center as the SOHO satellite.

5 Previous famous events

This section gives examples of a few "famous" events the last ten years. A large event in March 1989 is famous for it's tremendous impact on daily life on the Earth. Two more recent events in 1997 were both regarded as relatively minor storms. However, these events were unique in one respect since they were intercepted by a fleet of satellites that tracked its every move, from the the first hint of activity on the Sun to the passage through space, over the Earth, and beyond. They gave researchers their first coherent picture of how a magnetic cloud interacts with the Earth's magnetic field.

5.1 March 1989 event

In March 1989 a large sunspot rotated into the disk of the Sun and started to emit powerful flares and was the start of one of the most spectacular geomagnetic storm we ever seen in modern times.

At 2:44 a.m Eastern Standard Time on March 13th, a particularly vigorous magnetic storm tripped the circuit breakers at James Bay generating station. A cascade of broken circuits rippled around the province, cutting off the rest of Hydro-Quebec's generators. In all, it had taken less than 90 seconds for power to collapse in the entire grid. The lights went out in Montreal and nearly all of Quebec at 2:46 a.m. Elevators stalled, traffic lights stopped, and homes cooled in the winter night. The people in Montreal woke up to cold houses, closed subway, confused traffic, and a paralyzed airport. The regional power company, Hydro-Quebec, restored power slowly, with priority to hospitals, police, and fire stations. By 10 a.m. 50% of the service had been restored, yet outages remained until near midnight. Powergrid failures also occured in Ontario, British Columbia, and Sweden. Local power systems other places in USA had also short outages or burnouts.

The solar flare affected much more than just electric power. Extreme conditions in the Earth's ionosphere prevailed for many days, so that radio communication failed. This stopped marine and navigational signals worldwide and disrupted all kinds of telecommunications. California Highway Patrol messages overpowered local transmission in Minnesota. Automatic garage doors in California suburb began to open and close without apparent reason. Micro-chip production in the northeastern United States stopped several times due to the ionospher's magnetic activity. Spectacular aurora were seen as far south as the Florida Key's.

The loss to Hydro-Quebec was in excess of 10 million US dollars and the overall Quebec businesses directly lost tens of millions of dollars due to stopped production, spoiled production, and idle workers. Commercial satellites were also hard hit – with malfunctions, burned circuits, loss of altitude control fuel, and reduced orbital lifetimes. All this is a lot of monetary damage from a single violent solar feature.

5.2 January 1997

On January 6-7 the LASCO instrument on SOHO observed a halo around the Sun indicating that a CME had erupted and was directed toward the Earth. This was the first such event that had been observed since the launch of SOHO in 1995. From the projected velocity of the particle cloud the flow speed toward the Earth was estimated to 450 km/s, thus a relatively slow CME. Figure 12 illustrates how the magnetic cloud propagated toward the Earth.

Just on time (derived from the estimated velocity) the SOHO/CELIAS instrument observed the in-situ changes in the solar wind parameters on January 10. The solar wind speed and density both show a sudden rise at about 0010 UT (wind speed from 350 km/s to 430). Then there is a second jump at 0430 UT, when the speed again rises, to 520 km/s for a couple of hours, then slowly returns to its pre-event value. A few minutes later, the WIND satellite instruments also experience the effect of the event. The event was followed through the magnetosphere, to the ionosphere and to the ground. The magnetospheric response quickly followed, resulting in wonderful auroral activity captured by the POLAR imagers, and well-correlated with ground-based magnetometer observations.

The big bubble of solar particles hit Earth's magnetic field, mashed it briefly toward the planet's surface (and toward the orbital altitudes of some satellites) like a fist hitting a balloon, engulfed Earth and rolled on into interplanetary space. WIND data showed that the cloud was almost 50 million kilometers thick. It kicked up the energy intensity in Earth's natural radiation belts to more than 100 times normal, where it remained for several days.

Magnetic Cloud Event January 7-11 1997

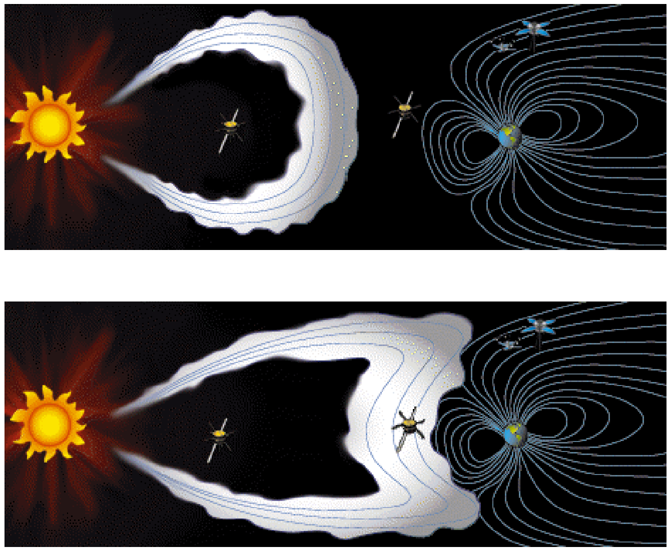

Figure 12: Illustration showing how the magnetic cloud propagated toward the Earth during the January 6-11 event (Courtesy of ISTP).

First the cloud of highly energetic electrons and protons poured energy into the magnetosphere, releasing energy explosively as magnetic sub-storms and pumping up the radiation belts. Then, early on Jan. 11, unexpectedly, a "huge pressure pulse" at the trailing edge of the bubble hit Earth. It was during this last event that the AT&T Telestar 401 satellite – located in the affected area of the magnetic field – suddenly fell silent, cutting TV coverage to millions of U.S. viewers. Six days later, after unsuccessful attempts to reestablish contact, the company declared it permanently out of service.

The magnetic storm triggered by the event hit the south polar region early on the morning of January 10. According to the British Antarctic Survey this event disrupted all communications and grounded aircraft for much of the day.

5.3 April 1997

A flare and a CME were observed by the EIT and LASCO instruments on the Solar and Heliospheric Observatory (SOHO) at 14:00 UT on April 7. The flare was also recorded by the GOES geosynchronous satellites in agreement with the SOHO EIT and Yohkoh X-ray images. Figure 13 shows a sequence of images recorded by the LASCO C2 coronagraph which reveal the big coronal mass ejection. The first frame shows the corona just before the eruption. The first stage of the eruption is seen in the upper right-hand corner. The eruption proceeds into a "halo" event and in the fourth image one can see a brightening around the entire sun, instead of in just one direction. Material ejected in this event reached the Earth in the night of April 10-11. A significant amount of geomagnetic activity was observed in northern regions all over the world, reaching as far south as New Hampshire and Montana. Eyewitness reports of aurora in New Hampshire and in Boston (Massachusetts) on the evening of April 10. Enhanced aurora was also observed from different satellites orbiting the Earth. The NASA Hubble Space Telescope was put into *safe mode* during

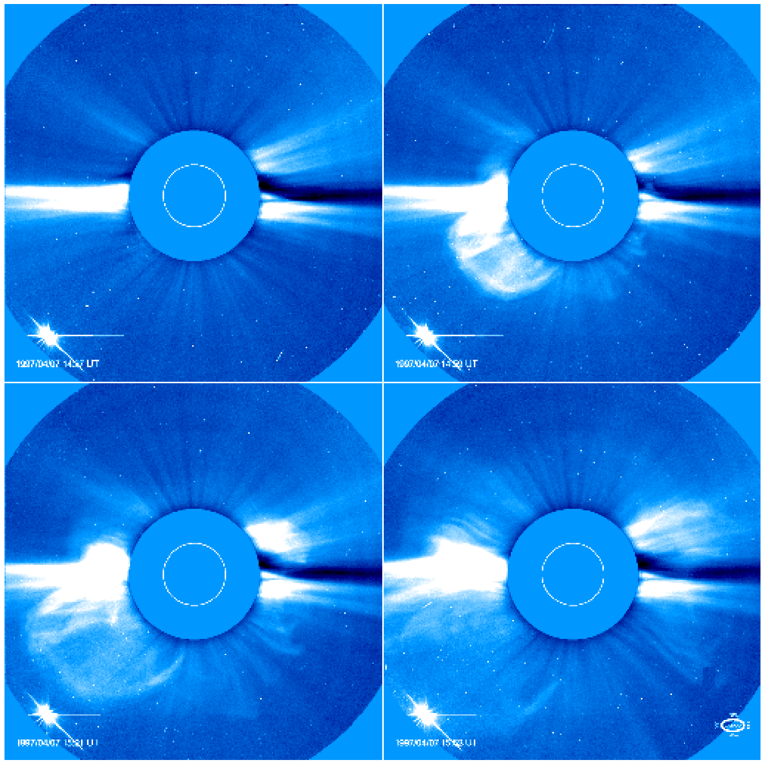

Figure 13: Sequence of images recorded by the LASCO C2 coronagraph showing the big coronal mass ejection of April 7, 1997 (Courtesy of SOHO/LASCO consortium).

this particular event.

6 Future prospects

The two events in 1997 could not be classified as large events by solar standards. However, for the first time we were able to see the birth of a space storm and have sufficient instruments in place to follow its effects all the way from the explosion on the Sun to the final dumping of gigawatts of energy into the polar regions of the Earth. Figure 14 illustrates the relative location of some ISTP satellites during the Sun-Earth event in January 1997. Some 20 satellites stationed around the Earth and out to the Sun, as well as 30 ground-based instruments around the globe, were used by scientist from a dozen countries to monitor the event for the International Solar Terrestrial Physics Program (ISTP).

Prediction of geomagnetic storms based on observation of events on the Sun only will have a high degree of error, since we presently can not accurately model the direction of the interplanetary magnetic field and the speed of the disturbance. The presence of the two satellites locates in the libration point (SOHO and ACE) will definitely improve the accuracy of space weather forecast. In addition they will improve our knowledge about the mechanisms that produces solar storms (flares and CMEs) and how the shock front traverse through interplanetary space before it hits the Earth's environment.

We are now approaching a new solar maximum. The last solar minimum was reached sometime

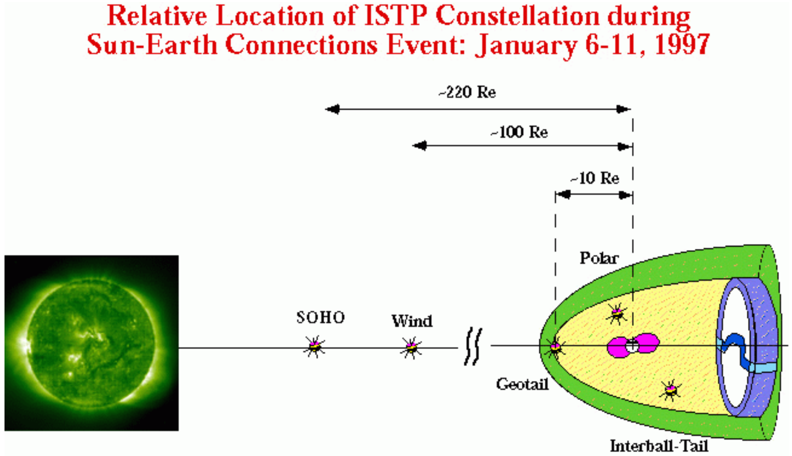

Figure 14: The relative location of some ISTP satellites during the Sun-Earth event in January 1997 (Courtesy of ISTP)

late 1996 and we have just started on cycle 23. An increasing number of active regions from the new cycle have started to appear and the number of flares and CMEs will continue to increase the next few years, as will the strength of the events.

A daily index of geomagnetic activity (called the daily A-index) has a scale from 0 to 400. Typical values for minimum conditions are of the order of 5-10 as can be seen in Figure 15 which covers the period of August 2 to October 2, 1997. On one occasion the A-index reached a value of 40 in this period. In this figure also gives the Sunspot number and the solar flux. The most intense storm of the last 10 years was in March, 1989, when the index was 246. There has been one geomagnetic storm a year for the last three years where the A-Index reach ed 50 or greater. When the new solar cycle gets to high levels beginning probably early in 1999, such conditions may occur several times per month during the most active months. The K-index (see section 4) during the March 1989 event had several values of 8 and 9. The solar proton radiation was about 100,000 times larger than normal during this event.

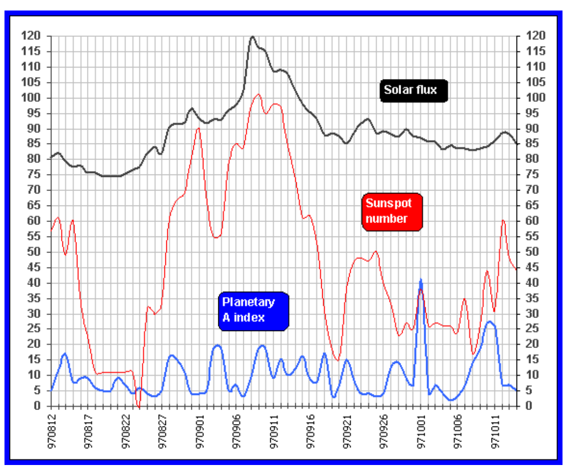

Figure 15: The variation of the solar flux, sunspot number, and the daily A-index for the period 2 August – 2 October 1997 (Courtesy of Jan Alvestad).

One important issue for the next solar maximum is that our society is much more sensitive to space weather activity today compared to the last solar maximum in 1991. This could be a major concern for the coming solar maximum in 2000-2001.

7 Acknowledgments

Front page graphic was made by Steele Hill, NASA Goddard Space Flight Center.

8 Appendix 1: Added information on solar flares

Under some conditions large solar flares can also emit high energy charged particles (protons and heavy particles such as helium) in addition to the enhanced UV/x-ray radiation. The proton energies may reach a few hundred MeV and the heavy ion component ranges in energy from 10s of MeV/n to 100s of GeV/n. As with the galactic cosmic ray particles, the solar flare particles are attenuated by the earth's magnetosphere. These particles can cause upsets in the satellite electronics as mentioned in section 3.8

9 Appendix 2: High Energy particles

The following information relates to radiation damage due to high energy particles in the satellite environment. The following was taken from the SEECA (Single Event Effects Criticality Analysis) from NASA Goddars Space Flight Center.

Radiation damage to on-board electronics may be separated into two categories: total ionizing dose and single event effects. Total ionizing dose (TID) is a cumulative long-term degradation of the device when exposed to ionizing radiation. Single event effects (SEEs) are individual events which occur when a single incident ionizing particle deposits enough energy to cause an effect in a device. The main sources of energetic particles that are of concern to spacecraft designers are:

1. protons and electrons trapped in the Van Allen belts,
2. heavy ions trapped in the magnetosphere,
3. cosmic ray protons and heavy ions, and
4. protons and heavy ions from solar flares.

The levels of all of these sources are affected by the activity of the sun. Trapped ions do not have sufficient energy to penetrate the satellite and to generate the ionization in electronic parts necessary to cause SEEs. Also, electrons are not known to induce SEEs. Trapped protons however, can cause upsets and it is difficult to shield against the high energy protons that cause SEE problems within the weight budget of a spacecraft.

Galactic cosmic ray particles originate outside the solar system. They include ions of all elements from atomic number 1 through 92. The flux levels of these particles are low but, because they include highly energetic particles (10s of MeV/n E 100s of GeV/n) of heavy elements such as iron, they produce intense ionization as they pass through matter. As with the high energy trapped protons, they are difficult to shield against. Therefore, in spite of their low levels, they constitute a significant hazard to electronics in terms of SEEs.

As with the trapped proton population, the galactic cosmic ray particle population varies with the solar cycle. It is at its peak level during solar minimum and at its lowest level during solar maximum. The reason for this is that the shielding of the Earth's magnetic filed is more effective during solar maximum compared to solar minimum. The earth's magnetic field provides spacecraft with varying degrees of protection from the cosmic rays depending primarily on the inclination and secondarily on the altitude of the trajectory. However, cosmic rays have free access over the polar regions where field lines are open to interplanetary space.

Solar flare protons and heavy ions vary with the solar cycle. During the solar minimum phase, few significant solar flare events occur; therefore, only the seven active years of the solar cycle are usually considered for spacecraft mission evaluations.

9.1 Orbit Environments

There are extremely large variations in the SEE inducing flux levels that a given spacecraft encounters depending on its trajectory through the radiation sources. Some of the typical orbit configurations are discussed below

The most important characteristic of the environment encountered by satellites in *Low Earth Orbit (LEOs)* is that several times each day they pass through the proton and electron particles trapped in the Van Allen belts. The level of fluxes seen during these passes varies greatly with orbit inclination and altitude.

The amount of protection that the geomagnetic field provides a satellite from the cosmic ray and solar flare particles is also dependent on the inclination and to a smaller degree the altitude of the orbit. As altitude increases, the exposure to cosmic ray and solar flare particles gradually increases. However, the effect that the inclination has on the exposure to these particles is much more important. As the inclination increases, the satellite spends more and more of its time in regions accessible to these particles. As the inclination reaches polar regions, it is outside the closed geomagnetic field lines and is fully exposed to cosmic ray and solar flare particles for a significant portion of the orbit.

Under normal magnetic conditions, satellites with inclinations below 45 will be completely shielded from solar flare protons. During large solar events, the pressure on the magnetosphere will cause the magnetic field lines to be compressed resulting in solar flare and cosmic ray particles reaching previously unattainable altitudes and inclinations. The same can be true for cosmic ray particles during large magnetic storms.

Satellites in *Highly Elliptical Orbits (HEOs)* are similar to LEO orbits in that they pass through the Van Allen belts each day. However, because of their high apogee altitude (greater than about 30,000 km), they also have long exposures to the cosmic ray and solar flare environments regardless of their inclination. The levels of trapped proton fluxes that HEOs encounter depend on the perigee position of the orbit including altitude, latitude, and longitude. If this position drifts during the course of the mission, the degree of drift must be taken into account when predicting proton flux levels.

At geostationary altitudes (*Geostationary Orbits - GEOs*), the only trapped protons that are present are below energy levels necessary to initiate the nuclear events in materials surrounding the sensitive region of the device that cause SEEs. However, GEOs are almost fully exposed to the galactic cosmic ray and solar flare particles. Protons below about 40-50 MeV are normally geomagnetically attenuated, however, this attenuation breaks down during solar flare events and geomagnetic storms. Field lines that cross the equator at about 7 earth radii during normal conditions can be compressed down to about 4 earth radii during these events. As a result, particles that were previously deflected have access to much lower latitudes and altitudes.

10 Appendix 3: Sample Space Weather Outlook

Below follows a typical space weather forecast as given by the Space Environment Center every day. It describes the current conditions and the possibilities of solar flares and geomagnetic activity. The regions they refer to is different active regions visible on the solar disk, each which is given a specific number as they appear. Since we do not know the exact mechanisms that trigger CME's there is no information on these features in the outlook.

A typical brief message looks like this:

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Space Weather Outlook

SOLAR ACTIVITY IS EXPECTED TO BE LOW
TO MODERATE.  THE PROBABILITY FOR C-CLASS X-RAY EVENTS REMAINS HIGH
FOR REGIONS 8083, 8084, AND 8085, WITH THE POSSIBILITY FOR AN
ISOLATED M-CLASS EVENT FROM REGION 8085.

THE GEOMAGNETIC FIELD IS
EXPECTED TO BE QUIET TO UNSETTLED FOR THE NEXT 24 HOURS, WITH
UNSETTLED TO ACTIVE CONDITIONS ON DAY TWO, AND MOSTLY UNSETTLED ON
DAY THREE.
```

Are detailed outlook is also made available:

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:Product: Report of Solar-Geophysical Activity
:Issued: 1997 Sep 11 2210 UT
# Prepared jointly by the U.S. Dept. of Commerce, NOAA,
#Space Environment Center and the U.S. Air Force.
#
JOINT USAF/NOAA REPORT OF SOLAR AND GEOPHYSICAL ACTIVITY
SDF NUMBER 254 ISSUED AT 2200Z ON 11 SEP 1997

IA.  ANALYSIS OF SOLAR ACTIVE REGIONS AND ACTIVITY FROM  10/2100Z
TO 11/2100Z:  SOLAR ACTIVITY WAS VERY LOW. NO SIGNIFICANT FLARES
OCCURRED. REGIONS 8083 (S28W48), 8084 (N22W13), AND 8085 (S26E15)
HAVE ALL REMAINED RELATIVELY STABLE AND QUIET SINCE YESTERDAY.
REGION 8085 CONTINUES TO BE THE MOST COMPLEX AS A 25-SPOT 'FKI'
BETA-GAMMA GROUP.  IN ADDITION, NEW REGION 8086, A SIMPLE 'BXO' BETA
GROUP, WAS NUMBERED TODAY AS IT ROTATED AROUND THE EAST LIMB.

IB.  SOLAR ACTIVITY FORECAST:  SOLAR ACTIVITY IS EXPECTED TO BE LOW
TO MODERATE.  THE PROBABILITY FOR C-CLASS X-RAY EVENTS REMAINS HIGH
FOR REGIONS 8083, 8084, AND 8085, WITH THE POSSIBILITY FOR AN
ISOLATED M-CLASS EVENT FROM REGION 8085.

IIA.  GEOPHYSICAL ACTIVITY SUMMARY FROM 10/2100Z TO 11/2100Z:
THE GEOMAGNETIC FIELD HAS BEEN QUIET TO UNSETTLED FOR THE PAST 24
HOURS, EXCEPT FOR A SINGLE PERIOD OF ACTIVE CONDITIONS RECORDED AT
MIDDLE LATITUDES DURING THE INTERVAL 10/2100-2400Z. THE GREATER THAN
2 MEV ELECTRON FLUX RANGED FROM MODERATE TO HIGH.

IIB.  GEOPHYSICAL ACTIVITY FORECAST:  THE GEOMAGNETIC FIELD IS
EXPECTED TO BE QUIET TO UNSETTLED FOR THE NEXT 24 HOURS, WITH
```

UNSETTLED TO ACTIVE CONDITIONS ON DAY TWO, AND MOSTLY UNSETTLED ON DAY THREE.

III. EVENT PROBABILITIES 12 SEP-14 SEP

CLASS M	30/30/30
CLASS X	01/01/01
PROTON	01/01/01
PCAF	GREEN

IV. PENTICTON 10.7 CM FLUX

OBSERVED 11 SEP 109

PREDICTED 12 SEP-14 SEP 105/105/102

90 DAY MEAN 11 SEP 078

V. GEOMAGNETIC A INDICES

OBSERVED AFR/AP 10 SEP 017/019

ESTIMATED AFR/AP 11 SEP 010/012

PREDICTED AFR/AP 12 SEP-14 SEP 015/015-015/015-010/010

VI. GEOMAGNETIC ACTIVITY PROBABILITIES 12 SEP-14 SEP

A. MIDDLE LATITUDES

ACTIVE	20/30/15
MINOR STORM	10/15/05
MAJOR-SEVERE STORM	06/06/01

B. HIGH LATITUDES

ACTIVE	20/30/15
MINOR STORM	10/15/05
MAJOR-SEVERE STORM	06/06/01

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The Author

The author defended his Dr. Scient degree in Solar Physics at the Institute of Theoretical Astrophysics, University of Oslo in 1993. The topic of the thesis was analysis and interpretation of ultraviolet high resolution observations of the solar atmosphere obtained from space. He has worked as a research scientist at the Institute of Theoretical Astrophysics since 1993 until present. He was awarded a Fulbright Scholarship in 1994 and spent one year in USA as a visiting scientist at the *High Altitude Observatory*, National Center for Atmospheric Research, Boulder Colorado and at *NASA Goddard Space Flight Center - GSFC*, Greenbelt, Maryland. The latter was to participate in the preparation of the SOHO operation facility at GSFC. He is an associated scientist on CDS, one of the UV spectrometers on SOHO and is part of the science operation team and spends about 50the time at the SOHO operations center. He was elected as a member of the International Astronomical Union in 1994. Member of the American Astronomical Society from 1995.

General fields of investigation includes analysis and interpretation of solar (and stellar) UV spectra and images obtained with various space born instruments such as the High Resolution Telescope and Spectrograph – HRTS, UVSP (SMM), SOLSTICE (UARS) and the SOHO instruments. In particular to study dynamics and *hyper*–fine structure in the outher solar atmosphere. Development of of science software for HRTS spectrograms and for the Coronal Diagnostic Spectrometer (CDS) on SOHO has also been pursued to a large extent.

Any comments or suggestions would be appreciated, and can be directed to the author at the following addresses:

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